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NUMERICAL TOOLS FOR LIGHTNING PROTECTION OF WIND TURBINES

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ABSTRACT

The present paper presents the different numerical tools used for lightning protection analysis. Initially the risk assessment considering attachment point distribution and location of vulnerable points on the wind turbine will be discussed, where also the term Lightning Protection Coordination (LPC) is introduced. When these two tools have been used to place air terminations on blades and defining the necessary insulation levels of interior parts, the voltage and current distribution along the blade structure can be calculated. This will put restrictions on the blade design, and define locations and requirements to insulation levels, equipotential bondings, indirect effects protection etc. Finally the lightning current arrives to the nacelle, where the principles of modelling magnetic fields, induced voltages, required shielding of panels etc. will be discussed.

ACRONYMS AND SYMBOLS

CAD	Computer-Aided Design
CFC	Carbon Fibre Composites
EGM	Electro Geometrical Model
FEM	Finite Element Method
HV	High Voltage
LPC	Lightning Protection Coordination
LPS	Lightning Protection System

INTRODUCTION

According to the recent international standard on wind turbine lightning protection IEC 61400-24 (Ref 1), verification of turbine designs can be conducted using numerical tools previously verified against field data. The overall quest is to define some mathematical representations of the natural phenomena which can predict the lightning behaviour and be used as part of the initial risk assessment and to define the first iterations of the turbine design.

Several tools covering the two main concerns of a lightning strike to physical structures are treated in this paper.

Initially the method for calculating the attachment point distribution is described, a process that has been developed further since our first paper on the subject in 2007 (Ref 2). This tool is now regarded as a definition of the overall exposure, to be followed by the LPC evaluation describing the detailed designs of a blade LPS.

Secondly the current conduction phase becomes important, where the blade structure containing many conductive and parallel paths for the lightning current must be treated. Following strikes to the blades or to parts of the nacelle installations, the turbine nacelle containing the majority of the sensitive electronics will be exposed to electro-magnetic fields and partial lightning currents. The wiring will be exposed to induced voltages and current surges, which must be reflected by a durable selection of shielding and SPD installation.

Calculation of all the quantities, the attachment point distribution, the magnetic fields and the current distribution is performed with the commercially FEM software Comsol Multiphysics and CST for the indirect effects assessment.

ATTACHMENT POINT DISTRIBUTION

First the attachment process is dealt with by calculating the attachment point distribution on single turbines. The tools developed are based on the research by Becerra and Cooray (Ref 3) and defines the exposure to direct lightning strikes for different locations on the turbines. This attachment point distribution defines the maximum amplitude of the lightning current that can strike a specific point, and will therefore give comparable results with the EGM methods, but using far more advanced physical representations.

According to the latest version of the IEC 61400-24, the EGM are not applicable for wind turbine blades, and it is expected that once the numerical tools in the present paper become more common, they will be the industry standard.

Importing CAD geometries

All modelling concerns the matter of building the real world with a suitable mathematical representation. Concerning the FEM environment Comsol Multiphsyics, and the issues of simulating current and voltage distribution within physically confined objects, a CAD drawing from the manufacturer is typically available. Before the geometries on such a CAD drawing can be discretized into the FEM environment, a considerable amount of work must be conducted to precondition the geometries.

This preconditioning is conducted in SpaceClaim Engineer, a CAD tool specially designed to remove sliver faces, spikes, and other mathematical irregularities. The iterative process is handled by a live link between the two types of software, and enables the construction of a sound and realistic 3D model of the wind turbine in this case.

Modeling principle

Once the CAD model has been preconditioned, to the compromise where sufficient details are present to calculate accurately, and still limited to the level where a calculation is possible, the drawing is loaded into Comsol Multiphysics.

In the FEM environment the surroundings consisting of the ground or sea level at which the turbine is installed, the analysis volume surrounding the turbine, and electric fields experienced by the charge distribution in the cloud or the approaching leader are defined.

Secondly the numerical code developed in (Ref 4) and based on the principle in (Ref 3) is applied in Matlab, to control the simulations in Comsol Multiphysics. The outcome is a risk assessment of the areas on the wind turbine exposed to different ranges of lightning peak currents. The outcome is comparable with the outcome of the EGM methods, but since the present models are based on the physical relations rather than empirical geometrical conditions as the EGM, the results correlate better with field experience.

Attachment point modelling on blades

The tools can be used with a macroscopic approach to see which part of the turbine is exposed to certain strike amplitudes, but also on a smaller scale to determine the distribution of attachment points along the blade length for each i.e. 10 or 25 cm intervals. Fig. 1 shows the first outcome of such an attachment point analysis, where the coloured dots represent the tip of downward leaders at the moment when an upward leader is incepted from the turbine. In this particular study the focus was on the strikes to the tower and nacelle, and less concern was on the distribution along the blade length.

The attachment distribution is defined as the fraction of leaders attaching to a certain region divided by all attachments to the structure, for the number of leader origins and the selected prospective peak current. The tendency is clear, that the higher the lightning current amplitude, the larger part of the strikes goes to the blade tip, whereas lower amplitude lightning strikes can find their way to more inboard positions.

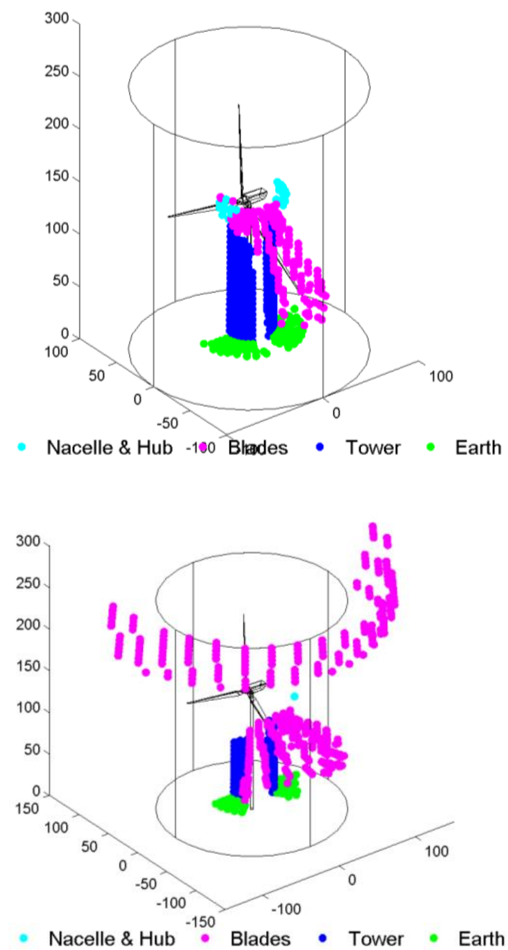

Fig 1 - Location of the tip of a downward moving leader at the moment of leader inception from the turbine. Top: 5kA, Bottom 10kA prospective peak current.

A second visualization of the use of the tool can be done by comparing the attachment point distribution of similar turbines with different blade lengths. The results are seen on Fig. 2, where the top two figures concerns a constant blade length with different amplitudes, and the bottom two figures concerns a constant amplitudes but with different blade lengths.

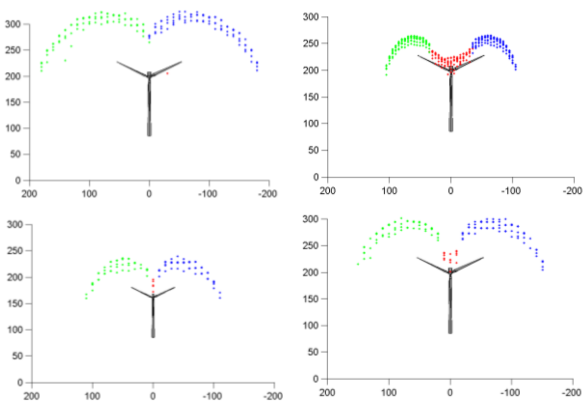

Fig 2 – Attachment point distribution. Top left: 60m blades 10kA, Top right: 60m blades 5kA, Bottom left: 40m blades 8kA, Bottom right: 60m blades 8kA.

The analysis is highly automated, and the quantitative results are used for defining the current levels to inject in the current and voltage distribution simulation of wind turbine blades.

LIGHTNING PROTECTION COORDINATION

The analysis denoted the *Attachment Point Distribution* defines the overall exposure of the blade design disregarding design details as insulation levels, receptor geometry, receptor spacing, presence of CFC, etc. Considering the actual performance of the blade during lighting exposure, these details are very important. If the insulation level of the blade shell and an internal insulated down conductor is very high, then the receptor spacing can also be considerably larger than for blade solution with a poor insulation level and an un-insulated down conductor.

The analysis principle is called *Lightning Protection Coordination* and is inspired by the insulation coordination known from the HV and Power industry. The full blade geometry cannot be imported for this level of detail, so blade sections no longer than 10m are typically considered. For these models, the blade skin, the receptor geometry, down conductor cable with or without insulation, CFC geometry, etc. are treated, and the individual materials are defined by the relative permittivity (ε_r), the electrical conductivity (σ) and the electrical breakdown strength [kV/mm].

After preconditioning and importing the CAD drawing of the geometry in question, the analysis is set up in Comsol Multiphysics and Matlab. Downward initiated strikes are simulated by a leader with prospective peak current of 3kA approaching from various origins and directions, whereas upward strikes are simulated by a static field increasing slowly in amplitude. In each case a stepwise static approach identifying the volumes of the geometry in which partial discharges takes place are evaluated. If the field strengths in the different materials exceed the breakdown field strengths, a puncture will occur and the insulation failure is a reality.

Fig. 3 and Fig. 4 show a blade geometry in 3D where a lightning leader of 3kA approaches. The leader is defined as a line charge distribution, which intensity increases for every iteration. For each iteration the field in every cell is compared with the breakdown field strength, and the material properties adjusted if the breakdown strength is exceeded. After 15 iterations a situation occurs where the upward leader is launched from the interior LPS of the blade, and punctures the blade skin.

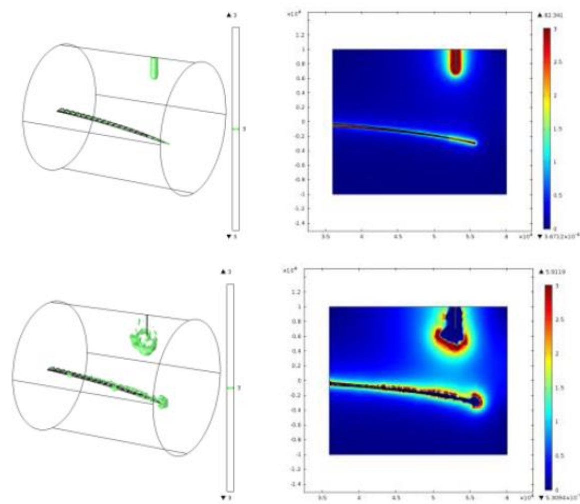

Fig 3 – Lightning Protection Coordination with a prospective peak current of 3kA, Iterative steps j=1 and j=5.

The situation is quite realistic if the insulation level of the blade skin and down conductor is too poor, and/or the receptor spacing is too large.

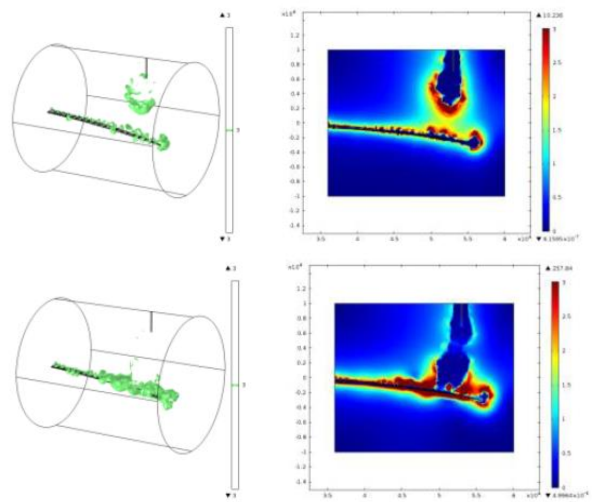

Fig 4 – Lightning Protection Coordination with a prospective peak current of 3kA, Iterative steps j=10 and j=15.

Further iterations on the blade design with repeated LPC simulations will eventually result in a design which most likely would pass the initial leader attachment test in the first round.

CURRENT AND VOLTAGE DISTRIBUTION IN BLADES

Once the blade is carefully designed such that all strikes attaches to the intended air terminations, the next step is to evaluate the voltage and current distribution between the different conductive elements within the blade. This especially becomes essential when several current paths are present in a blade (parallel down conductors, Carbon fibre structural parts, heating systems for de-icing, sensor and measurement equipment, etc.). This statement is not only presented as part of a natural design consideration, but has been stated at least since the IEC TR 61400-24 in 2002 (Ref 5), and lately in the revised IEC 61400-24 from 2010 (Ref 1).

In these official documents it is clearly stated that additional conductive components within the blades (CFC or wiring) must be protected by appropriate equipotential bonding, thereby avoiding internal sparks. By following an iterative procedure where the voltage and current distribution are modelled and equipotential bondings are applied at suitable places, the designer will eventually end with a system where internal sparks are avoided. Fig. 5 shows an example of how the first few meters of a blade could be subdivided in the lumped circuit element model.

Considering the rising flank of a subsequent stroke (Ref 1), the inductive voltage drop along a typical down conductor would be in the range of 160kV/m, clearly having an impact on the blade performance without carefully concerning the mutual couplings between different electrically conductive systems.

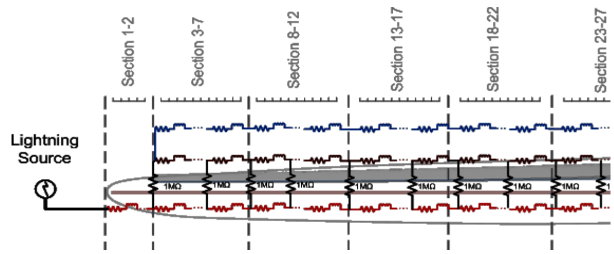

Fig 5 – Simplified lumped circuit element model of a wind turbine blade.

MAGNETIC FIELDS AND CURRENT DISTRIBUTION

Once the lightning discharge has been intercepted by the wind turbine, the lightning current will begin to flow along the designated down conductor path. Often this path goes via the structural components of the wind turbine nacelle (either due to an attachment to the blades or directly to the nacelle), and the partial currents and magnetic fields associated with this main lightning current will then induce voltages in wiring and nearby electronics.

The following section describes the methods developed to foresee this impact at a very early design stage of the wind turbine.

Importing CAD geometries

The correct geometry of the structure (nacelle) is again a prerequisite of getting a good result. As for the attachment point modelling, the CAD drawings supplied by the manufacturers needs to be preconditioned in Space Claim, to ensure the correct level of detail. Here unnecessary details regarding the overall magnetic field distributions are removed, i.e. threaded holes, sliver faces, non-conductive structures cables and minor panels. The assumption is that the current distribution is governed mostly by the major structural metal parts, and only to a limited extent to the internal wiring and cables.

Modelling principle

Once the structure has been defined, the modelling conditions in the FEM environment are set up. Current is injected along the designated down conductor path (from the attachment point at the blade tip or the nacelle to the tower bottom), and the current distribution among the different structural components as well as the magnetic field surrounding these components are calculated. Typically the standardized lightning pulses are injected, either in time domain or by considering the dominating frequency in the frequency domain.

Fig. 6 shows an example of the magnetic field distribution during first return stroke currents entering different places on the nacelle/hub.

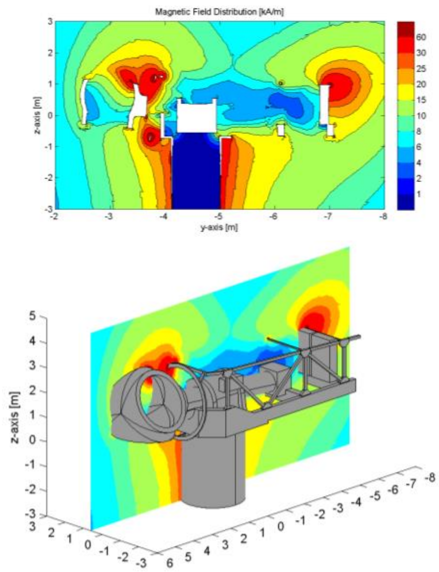

Fig. 6 - Magnetic field distribution within a nacelle structure used to assess the shielding requirements of control panels.

The magnetic field distribution for the currents distributed within the structural components, leads to analytical approaches or time domain simulations of induced voltages and currents. An example of the time domain simulation of the induced voltages and current components is seen in Fig. 7.

Using the analysis tools enables the designer at an early stage in the design to foresee proximity effects of the lightning protection system as an integrated part of the electrical design, to define requirements for transfer impedances on cable shields and EMC glands, specify the necessary attenuation of panels and cabinets, and therefore get closer to a design that will perform well during real life lightning conditions.

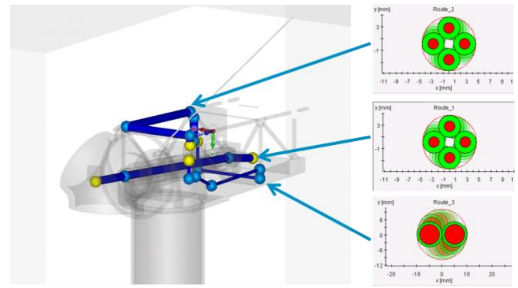

Fig. 7 - Induced voltage and currents in wind turbine nacelle installations, determined in time domain along different cable routings.

In IEC 61400-24 section 8.3.1 (Ref 1) it is required that the wind turbine nacelle is divided into lightning protection zones (LPZ). This zoning concept is to ensure that the designer has considered the coordination of the threat level, shielding, surge protection, etc. and that the equipment selected complies with the zone at which it is installed. Since the designer has to assume the threat level and also select a finite number of zones, the analysis is rather subjective. In many cases it is beneficial to evaluate the real exposure and environment, and thereby to post realistic requirements to the different components.

For this purpose, shielding of cables and panels, integration of surge protection and insulation coordination become very important. Fig. 8 shows an example of the assessment of the magnetic field levels within metal panels, to evaluate the necessity of special shielding or field attenuation.

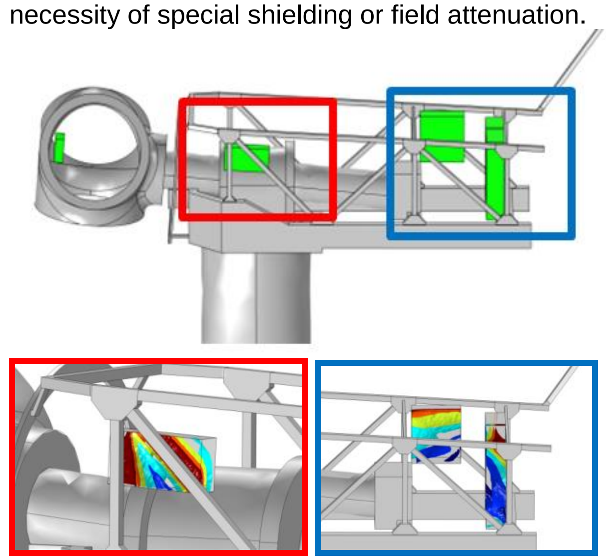

Fig. 8 - Simulation of the magnetic field impinging on electric panels.

Based on the results achieved in Fig. 8, the manufacturer can either chose to move the panel to a safer location, install equipment inside the panel that can withstand the environment, or increase the magnetic field attenuation of the panel itself.

STANDARDISATION

The purpose of all technical design and test standards are to present a reasonable state of the art and best practices within engineering, to be followed by all designers, manufacturers, sub-suppliers, etc. However, since there is a time lap between the writing of standards and the time of publication or even revisions, the content of the standards is not always completely up to date.

The purpose of this publication is to address the fact that there is research going on to improve the engineering tools within lightning protection. It is no longer costly or unreasonably memory consuming to conduct the numerical analysis mentioned in this paper, and it will definitely improve the basis for coordinating the lightning protection design properly.

Until the next revision of the IEC 61400-24, a considerable effort in improving the numerical tools will be made, such that they slowly but steadily can form a natural part of the verification process.

CONCLUSION

The paper has presented numerical tools used to foresee lightning attachment points, and enable the lightning protection coordination; all based on physics instead of the EGM methods. Secondly the consequence of having the lightning current flowing through the blades and the nacelle is investigated in terms of the current distribution and the magnetic fields.

In both cases these tools represent an alternative to the engineering methods given by the current standards, tools that will be sought implemented in future revisions of the IEC 61400-24.

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